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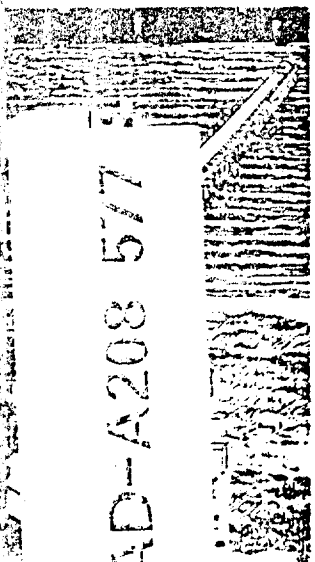

US Army Corps of Engineers

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-CO-9

STABILITY OF DOLOS OVERLAYS FOR REHABILITATION OF STONE-ARMORED RUBBLE-MOUND BREAKWATER HEADS SUBJECTED TO BREAKING WAVES

by

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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

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GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS:

TOP — Field research facility, Duck, North Carolina.

BOTTOM — Author delivers 42-ton dolos to Crescent City Harbor, California.

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

An experimental model investigation was conducted to obtain design guidance for dolos overlays used to rehabilitate stone-armored rubble-mound breakwater heads subjected to breaking waves. Based on model tests and prototype experience (Crescent City Harbor, and Humboldt Bay, California), the investigation concluded that:

a. Minimum stability was observed at the 45-deg wave direction.

b. Stability proved to be sensitive to both d/L and H/d with minimum stability occurring at the lower values of d/L and higher values of H/d, i.e., longer wave periods in shallower water.

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16. SUPPLEMENTARY NOTATION (Continued).

A report of the Coastal problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. This report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

19. ABSTRACT (Continued).

c. The stability coefficient appears to decrease slightly as the armor slope becomes flatter; therefore, the following values are recommended for sizing the dolos:

Structure Slope	Stability Coefficient
1V on 1.5H	8
1V on 2H thru 1V on 3.5H	7
1V on 4H thru 1V on 5H	6

PREFACE

Authority for the US Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), to conduct this study was granted by the Headquarters, US Army Corps of Engineers (HQUSACE), under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program Work Unit 32325 entitled "Use of Dissimilar Armor for Repair and Rehabilitation of Rubble-Mound Coastal Structures."

Head tests of dolos overlays for existing armor stone, which fulfill one milestone of this work unit, were conducted under the general guidance of Mr. James E. Crews, and Dr. Tony C. Liu, REMR Overview Committee, HQUSACE; Messrs. Jesse A. Pheiffer, Jr., Directorate of Research and Development, HQUSACE; John W. Lockhart, Coastal Technical Monitor, HQUSACE; and William F. McCleese, REMR Program Manager, WES, and D. D. Davidson, REMR Coastal Problem Area Leader, CERC.

The study was conducted by personnel of CERC under general direction of Dr. James R. Houston, Chief, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC. Direct supervision was provided by Messrs. C. Eugene Chatham, Chief, Wave Dynamics Division (CW), and D. D. Davidson, Chief, Wave Research Branch (CW-R). This report was prepared by Mr. Robert D. Carver, Principal Investigator. The report was edited by Mrs. Joyce H. Walker, Information Products Division, Information Technology Laboratory, WES. The model was operated by Messrs. C. Ray Herrington and Marshall P. Thomas, Engineering Technicians.

Acting Commander and Director of WES during preparation of this report was LTC Jack R. Stephens, EN. Dr. Robert W. Whalin was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
degrees (angle)	0.01745329	radians
feet	0.3048	metres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres

STABILITY OF DOLOS OVERLAYS FOR REHABILITATION OF STONE-ARMORED RUBBLE-MOUND BREAKWATER HEADS SUBJECTED TO BREAKING WAVES

PART I. INTRODUCTION

Background

1. The experimental investigation described herein constitutes a portion of a research effort to provide engineering data for the effective and economical rehabilitation of rubble-mound breakwaters and jetties. In this study, a rubble-mound breakwater is defined as a protective structure constructed with a core of quarry-run stone, sand, or slag and protected from wave action by one or more stone underlayers and a cover layer composed of selected quarrystone of specially shaped concrete armor units.

2. Previous investigations, including work performed under Work Unit 31269, "Stability of Breakwaters" have yielded a significant quantity of design information for (a) quarrystone (Hudson 1958 and Carver 1980, 1983); (b) quadripods, tribars, modified cubes, hexapods, and modified tetrahedrons (Jackson 1968); (c) dolosse (Carver and Davidson 1977 and Carver 1983); and (d) toskane (Headquarters, US Army Corps of Engineers 1978). Rehabilitation projects on several of the Corps rubble-mound structures have revealed a total lack of design guidance or even information concerning the interfacing and stability response of armor units that are of dissimilar type and/or size. In the past, selection of new armor type and method of interfacing have been based on engineering judgment or, more recently, on site-specific model studies. Site-specific model studies have provided good singular solutions, but their results are generally not applicable to other projects (Carver, in preparation). It is anticipated that the problem will become more acute in future years as rehabilitation of major breakwaters and jetties becomes necessary to extend their project life or to meet greater design demands.

Approach

3. In this study, model breakwaters and armor units have been used to

experimentally investigate the stability response of various armor combinations for selected structure geometries and wave conditions. Because of the effort involved in comprehensively investigating all different types of existing armor units, this research effort concentrated on the three types of armor most commonly used by the Corps--stone, dolos, and tribars. Results of trunk tests of dolos and tribar overlays of existing stone armor, dolos overlays of existing dolos, and dolos overlays of existing tribars have been reported (Carver and Wright 1988a, 1988b, and 1988c).

Purpose of Study

4. The purpose of the present investigation is to obtain design guidance for dolos overlays used to rehabilitate stone-armored rubble-mound breakwater and jetty heads subjected to breaking waves. More specifically, it is desired to determine the minimum weight of individual armor units (with given specific weights) required for stability as a function of angle of wave attack, wave period, wave height, and water depth.

PART II: TESTS

Stability Scale Effects

5. If the absolute sizes of physically modelled breakwater materials and wave dimensions become too small, flow around the armor units enters the laminar regime, and the induced drag forces become a direct function of the Reynolds number. Under these circumstances prototype phenomena are not properly simulated, and stability scale effects are induced. Hudson (1975) presents a detailed discussion of the design requirements necessary to ensure the preclusion of stability scale effects in small-scale breakwater tests and concludes that scale effects will be negligible if the Reynolds stability number (R_n)

$$R_N = \frac{g^{1/2} H^{1/2} l_a}{\nu} \qquad (1)$$

where

g = acceleration due to gravity, ft/sec^2

H = wave height, ft

l_a = characteristic length of armor unit, ft

ν = kinematic viscosity

is equal to or greater than 3×10^4.* For all tests reported herein, the sizes of experimental armor and wave dimensions were selected such that stability scale effects were insignificant (i.e., R_N was greater than 3×10^4). Froude similarity was maintained in scaling wave conditions.

Test Procedures

Method of constructing test sections

6. All experimental breakwater sections were constructed to reproduce as closely as possible results of the usual methods of constructing full-scale breakwaters. The core material was dampened as it was dumped by bucket or

* For convenience, symbols and abbreviations are listed in the Notation (Appendix A).

sh .el into the flume and was compacted with hand trowels to simulate natural consolidation resulting from wave action during construction of the prototype structure. Once the core material was in place, it was sprayed with a low-velocity water hose to ensure adequate compaction of the material. The under-layer stone was than added by shovel and smoothed to grade by hand or with trowels. Armor units used in the cover layers were placed in a random manner corresponding to work performed by a general coastal contractor; i.e., they were individually placed but were laid down without special orientation or fitting. After each test, the armor units were removed from the breakwater, all of the underlayer stones were replaced to the grade of the original test section, and the armor was replaced.

Test Equipment and Materials

Equipment

7. All stability tests were conducted in an L-shaped concrete flume 250 ft* long, 50 and 80 ft wide at the top and bottom of the L, respectively, and 4.5 ft deep (Figure 1). The flume is equipped with a flap-type wave generator. Tests were conducted with monochromatic waves. Changes in water surface elevation as a function of time (wave heights) were measured by electrical wave height gages in the vicinity of where the toe of the test sections was to be placed. Electrical output of the wave gages was directly proportional to their submergence depth. Test sections were constructed at the top of the 1V on 35H bottom slope.

Material

8. Rough, hand-shaped granitic stone with an average length of approximately two times its width, average weight of 0.55 lb, and a specific weight of 167 pcf was used to simulate existing armor stone. Dolos overlays were composed of 0.276-lb units that have a specific weight of 142.2 pcf. Sieve-sized limestone (specific weight = 165 pcf) was used for the underlayers and core.

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

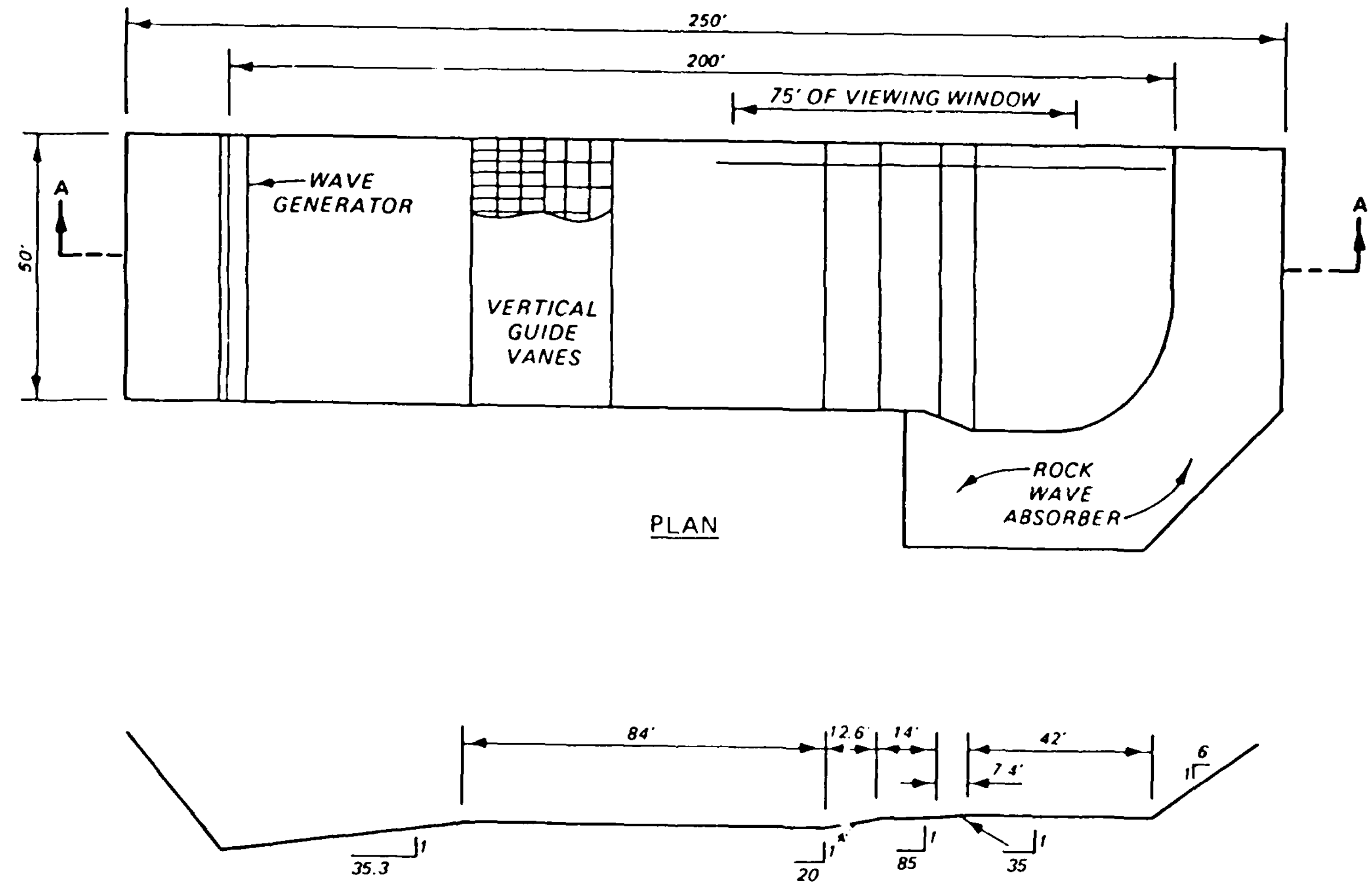


Figure 1. Layout of the L-shaped flume

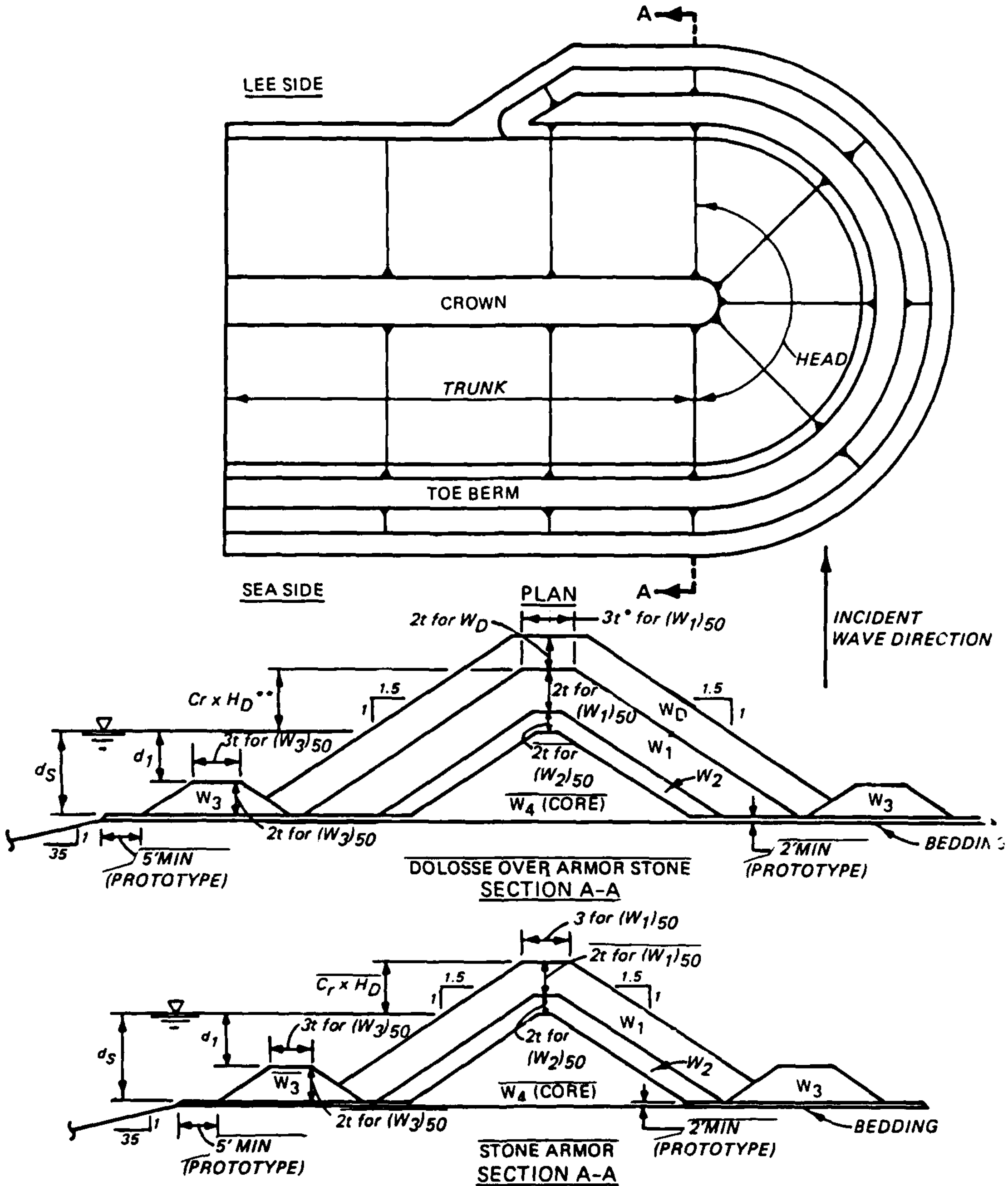
Selection of Test Conditions

9. By nondimensionalizing design conditions from site-specific projects, it was found that a d/L range of 0.04 to 0.12 should include most prototype conditions encountered in breaking-wave stability designs. A review of capabilities of the available wave flumes and generators showed that this range of d/L values could be achieved for a reasonable range of testing depths.

10. The wave flume was calibrated (paddle stroke was determined as a function of wave height) for depths of 0.40, 0.50, and 0.60 ft at d/L values of 0.04, 0.06, 0.08, 0.10, and 0.12. This range of depths and consequently breaking wave heights proved to be compatible with the selected armor weights and breakwater slopes.

11. Each test wave condition was allowed to attack the breakwater for a cumulative period of 30 min, then the test sections were rebuilt prior to attack by the next wave condition. This 30-min interval allowed sufficient time for the test sections to stabilize, i.e., time for all significant movement of armor material to abate. During tests, the wave generator was stopped as soon as reflected waves from the breakwater returned to the paddle, and the waves were allowed to decay to zero height before restarting the generator to prevent the test sections from being exposed to uncontrolled wave groups and/or an undefined wave spectrum.

12. All tests were conducted on conical head sections of type shown in Figure 2. Results of previously conducted nonbreaking wave head tests (Carver, Herrington, and Wright 1987) are graphically summarized in Figure 3. These data show angles of wave attack of 45 and 90 deg (wave crests parallel to the structure) to be the most critical for nonbreaking waves. Therefore, these wave directions were selected for use in the present investigation.

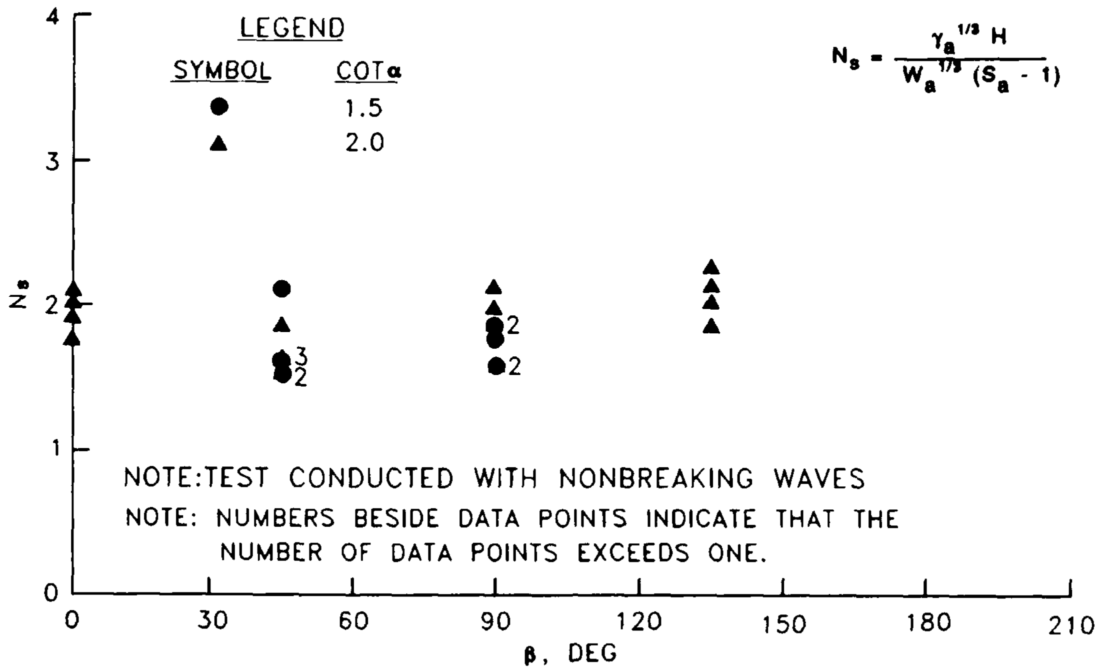


W_D = DOLOS OVERLAY (W_D = 0.276 LB)
W_1 = PRIMARY ARMOR ($(W_1)_{50}$ = 0.38 OR 0.55 LB STONE)
W_2 = UNDERLAYER ($(W_2)_{50}$ = 1/10 $(W_1)_{50}$
W_3 = TOE BERM STONE ($(W_3)_{50}$ RANGED FROM 0.55 TO 0.055 LB; WEIGHT VARIED WITH d_S AND H_D)
W_4 = CORE AND BEDDING STONE ($W_4 = W_1/200$ TO $W_1/4000$

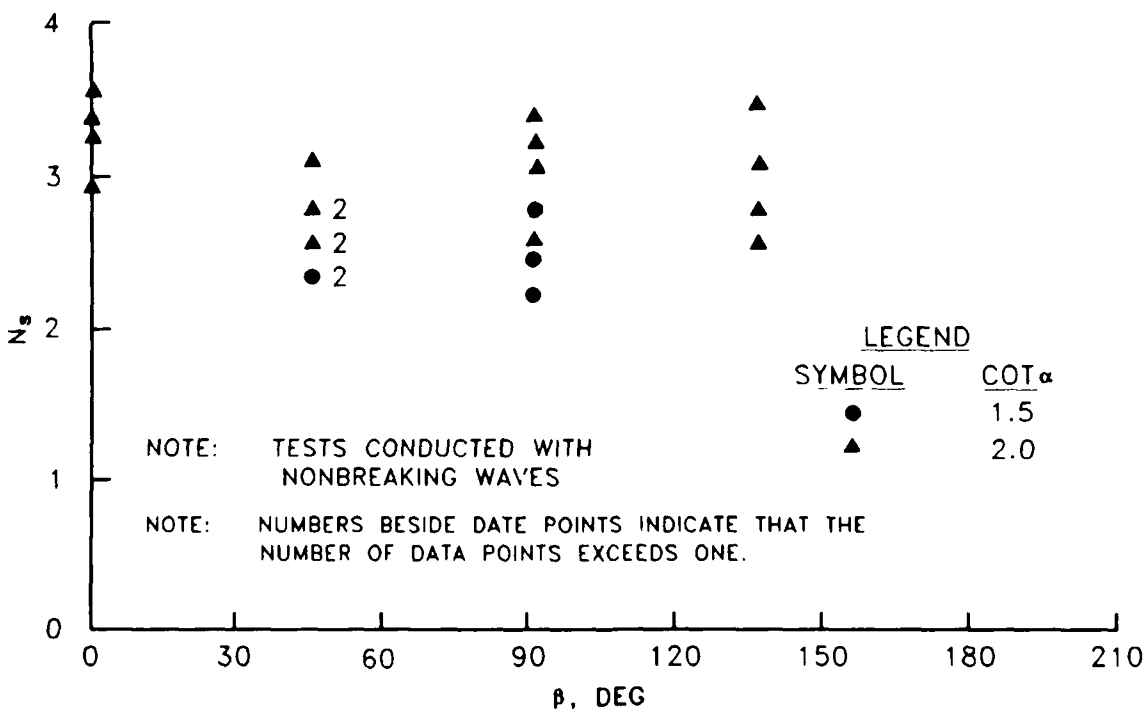
* $t = k_\Delta (W/\gamma)^{1/3}$, WHERE k_Δ = 1.0 FOR ROUGH ANGULAR STONE AND 0.94 FOR DOLOSSE AND $W = W_{50}$

** CREST HEIGHT SET AT $C_r X H_D$ ABOVE MAXIMUM SWL, WHERE H_D IS DESIGN WAVE HEIGHT ASSOCIATED WITH MAXIMUM SWL AND C_r IS MAXIMUM RUNUP COEFFICIENT FOR MAXIMUM SWL DESIGN CONDITIONS. C_r = 0.80 FOR DOLOSSE AND C_r = 1.0 FOR STONE ARMOR

Figure 2. Typical test section



a. Stone armor



b. Dolos armor

Figure 3. Stability number N_s versus angle of wave attack β

PART III: TEST RESULTS

Seaside Structure Slope = 1V on 1.5H

13. Stability test results for dolos overlays constructed on a 1V on 1.5H slope are summarized in Table 1. Presented therein are experimentally determined K_D values as functions of angle of wave attack β, relative depth d/L, and relative wave height H/d. Wave heights were measured at the toe of the structure without the structure in place and the wave length was calculated using Airy theory and the water depth at the toe of the breakwater. The stability coefficient K_D is determined from the Hudson formula, i.e.,

$$W_a = \frac{\gamma_a H^3}{K_D (S_a - 1)^3 \cot \alpha} \qquad (2)$$

where

K_D = stability coefficient

S_a = specific gravity of armor unit

α = reciprocal of breakwater slope

Armor units were placed randomly in two layers and the number of armor units per surface area was equal to that presently recommended for new construction in EM 1110-2-2904, "Design of Breakwaters and Jetties" (Headquarters, Department of the Army 1986). Photos 1-6 show typical after-testing conditions of the structures. As evidenced in these photos, design wave conditions allowed occasional random displacement of a few random armor units; however, movement was never extensive enough to jeopardize the stability of the test section.

14. Figure 4 presents the stability coefficient as a function of angle of wave attack. These data show that 45-deg wave attack generally produced slightly lower stability than that observed for 90-deg wave attack; however, the minimum stability coefficient was the same for both wave directions. Figures 5 and 6 depict stability as a function of d/L and Figures 7 and 8 show the effects of H/d. These data indicate that stability is sensitive to both d/L and H/d with minimum stability occurring at the lower values of d/L and higher values of H/d, i.e., longer wave periods in shallower water.

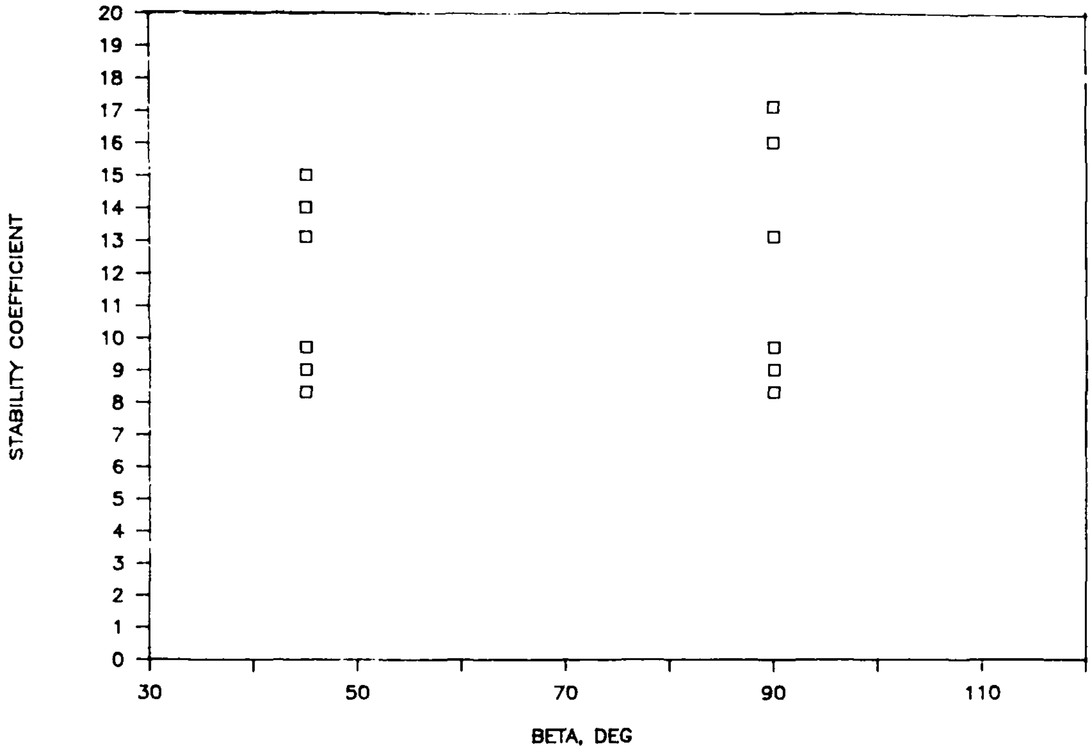


Figure 4. Stability coefficient as a function of angle of wave attack, 45 and 90 deg angles

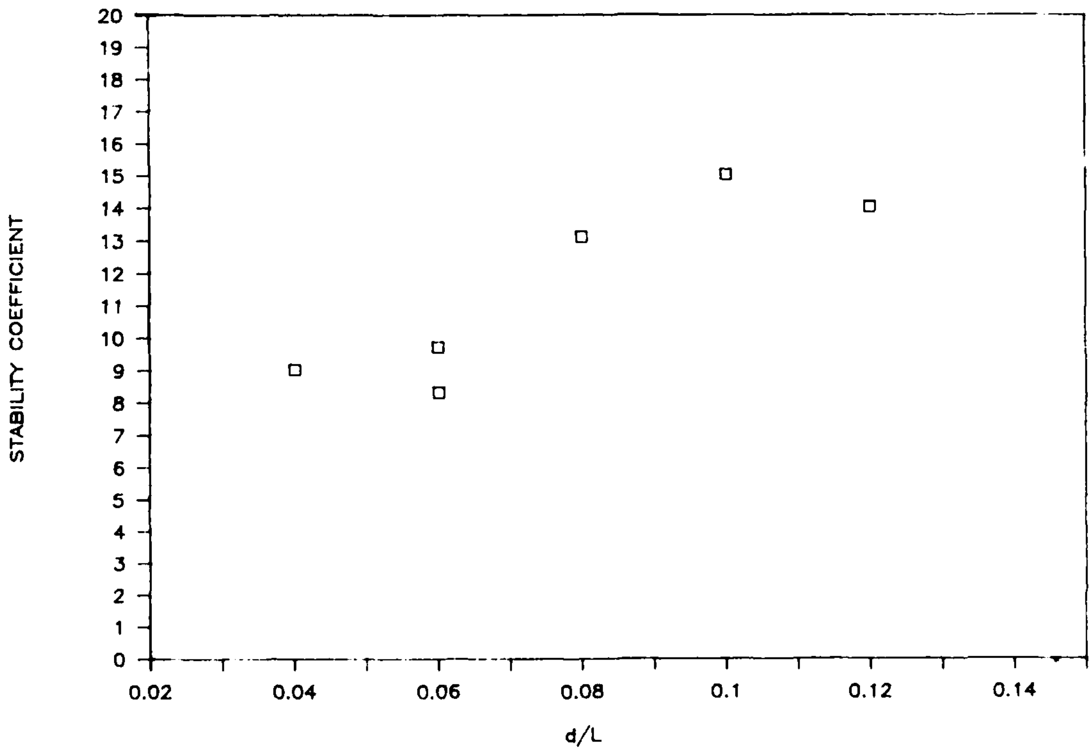


Figure 5. Stability as a function of d/L , 45-deg angle of wave attack

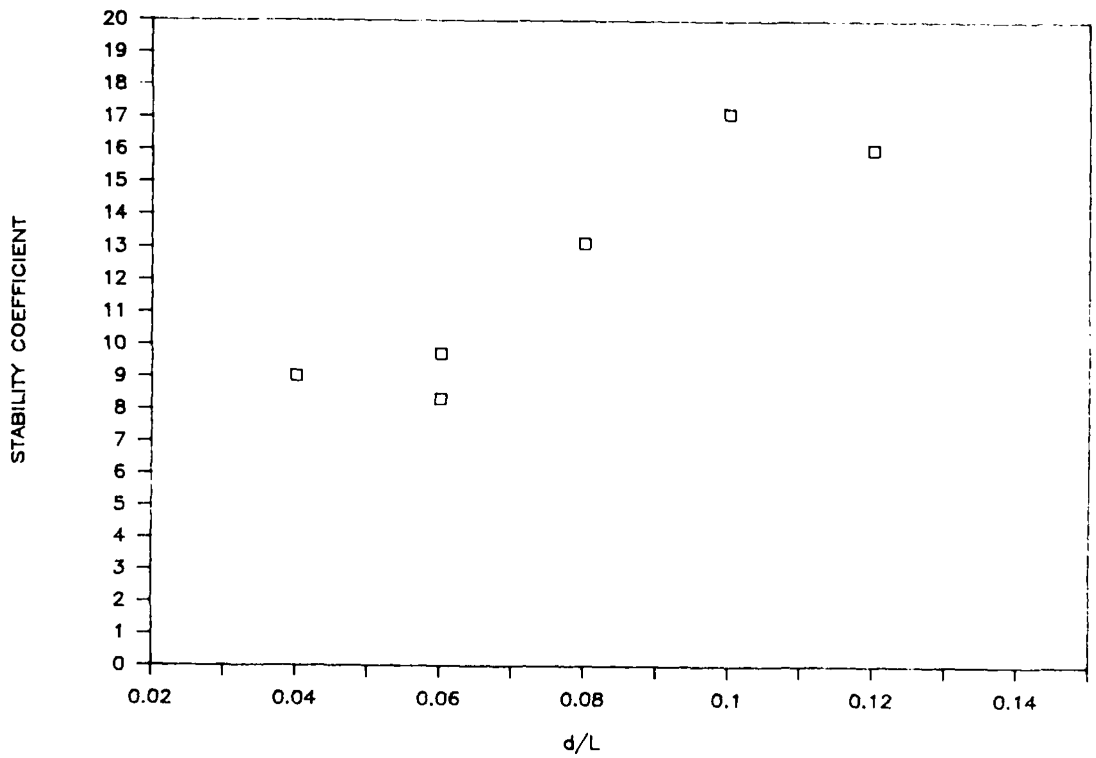


Figure 6. Stability as a function of d/L , 90-deg angle of wave attack

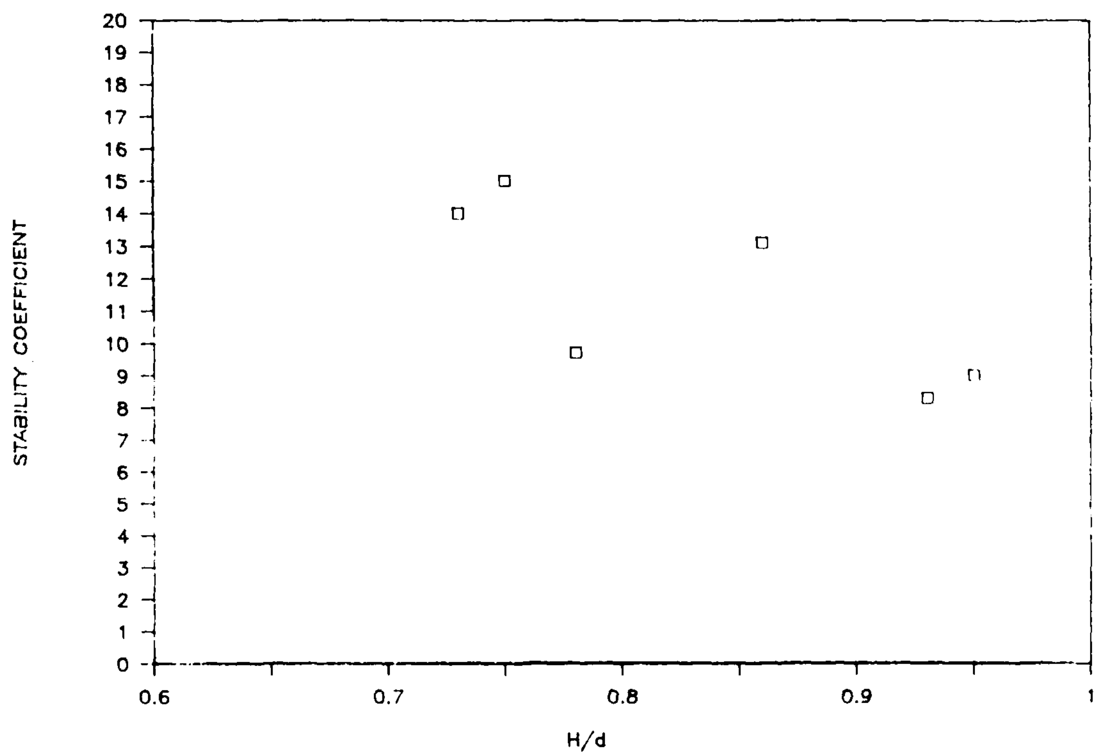


Figure 7. Effects of H/d , 45-deg angle of wave attack

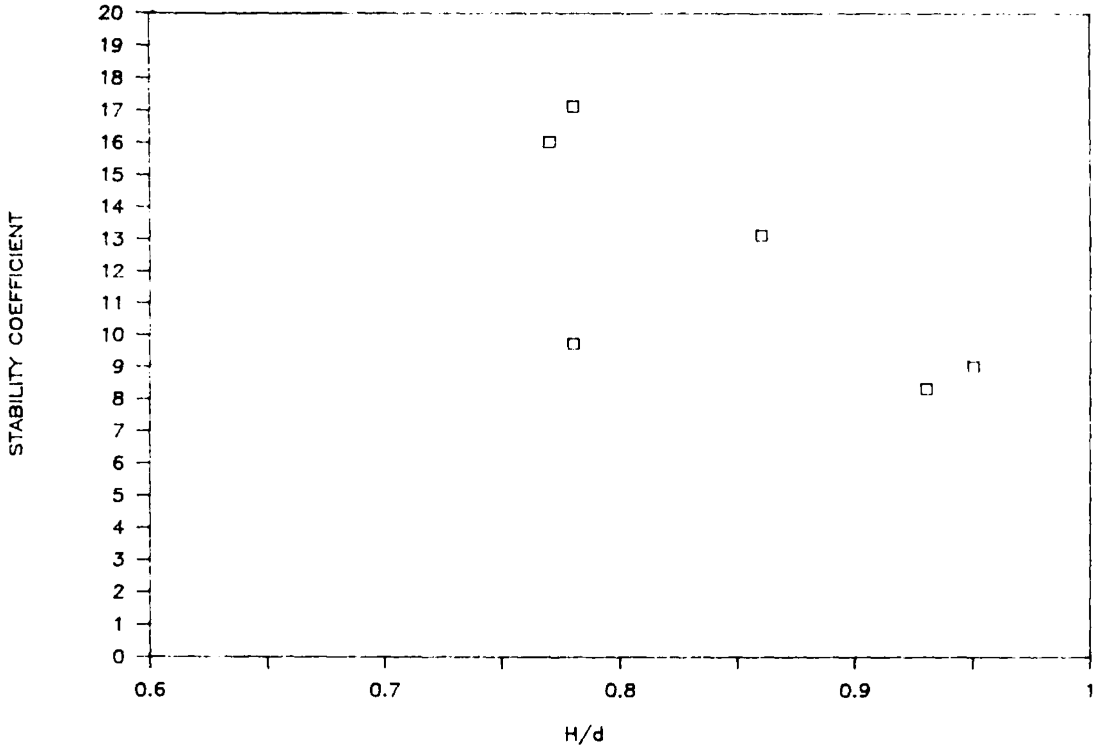


Figure 8. Effects of H/d , 90-deg angle of wave attack

These trends are consistent with those observed for dolos used in new construction (Carver (1983)).

Site-Specific Studies

15. A site-specific investigation of dolos overlays for structure heads was conducted for Humboldt Bay, California, by Davidson (1971). Also, dolos overlays for breakwater repair at Crescent City, California, were tested by Baumgartner, Carver, and Davidson (1985). The Crescent City repair was developed for use at an elbow; however, due to the multiple wave directions tested, results should be generally applicable to structure heads. Structure slopes at Humboldt Bay and Crescent City ranged from 1V on 4H to 1V on 5H, and test results yielded stability coefficients in the 6.0 to 8.0 range.

Discussion and Recommendations

16. Results from Crescent City Harbor, Humboldt Bay, California, when taken in concert with tests presented herein, show the stability coefficient

appears to decrease slightly as the armor slope becomes flatter. Therefore, the following values are recommended for sizing the dolos:

Structure Slope	Stability Coefficient
1V on 1.5H	8
1V on 2H thru 1V on 3.5H	7
1V on 4H thru 1V on 5H	6

PART IV: CONCLUSIONS

17. Based on model tests and prototype experience (Crescent City Harbor, and Humboldt Bay, California) described herein in which dolos armor is used to overlay existing armor stone on breakwater heads subjected to breaking waves, it is concluded that:

- a. The 45-deg wave direction generally produced slightly lower stability than that observed for 90-deg wave attack; however, the minimum stability coefficient was the same for both wave directions.
- b. Stability proved to be sensitive to both d/L and H/d with minimum stability occurring at the lower values of d/L and higher values of H/d, i.e., longer wave periods in shallower water.
- c. The stability coefficient appears to decrease slightly as the armor slope becomes flatter; therefore, the following values are recommended for sizing the dolos:

Structure Slope	Stability Coefficient
1V on 1.5H	8
1V on 2H thru 1V on 3.5H	7
1V on 4H thru 1V on 5H	6

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Table 1

Values of T, H, d/L, H/d, and K_D for Dolos Armor Overlays of Existing Stone Armor on Breakwater Heads and Subjected to Breaking Waves; 1V on 1.5H Structure Slope

β, deg	d, ft	T, sec	H, ft	d/L	H/d	K_D
45	0.40	1.90	0.37	0.06	0.93	8.3
45	0.40	2.82	0.38	0.04	0.95	9.0
45	0.50	1.62	0.43	0.08	0.86	13.1
45	0.50	2.12	0.39	0.06	0.78	9.7
45	0.60	1.24	0.44	0.12	0.73	14.0
45	0.60	1.45	0.45	0.10	0.75	15.0
90	0.40	1.90	0.37	0.06	0.93	8.3
90	0.40	2.82	0.38	0.04	0.95	9.0
90	0.50	1.62	0.43	0.08	0.86	13.1
90	0.50	2.12	0.39	0.06	0.78	9.7
90	0.60	1.24	0.46	0.12	0.77	16.0
90	0.60	1.45	0.47	0.10	0.78	17.1

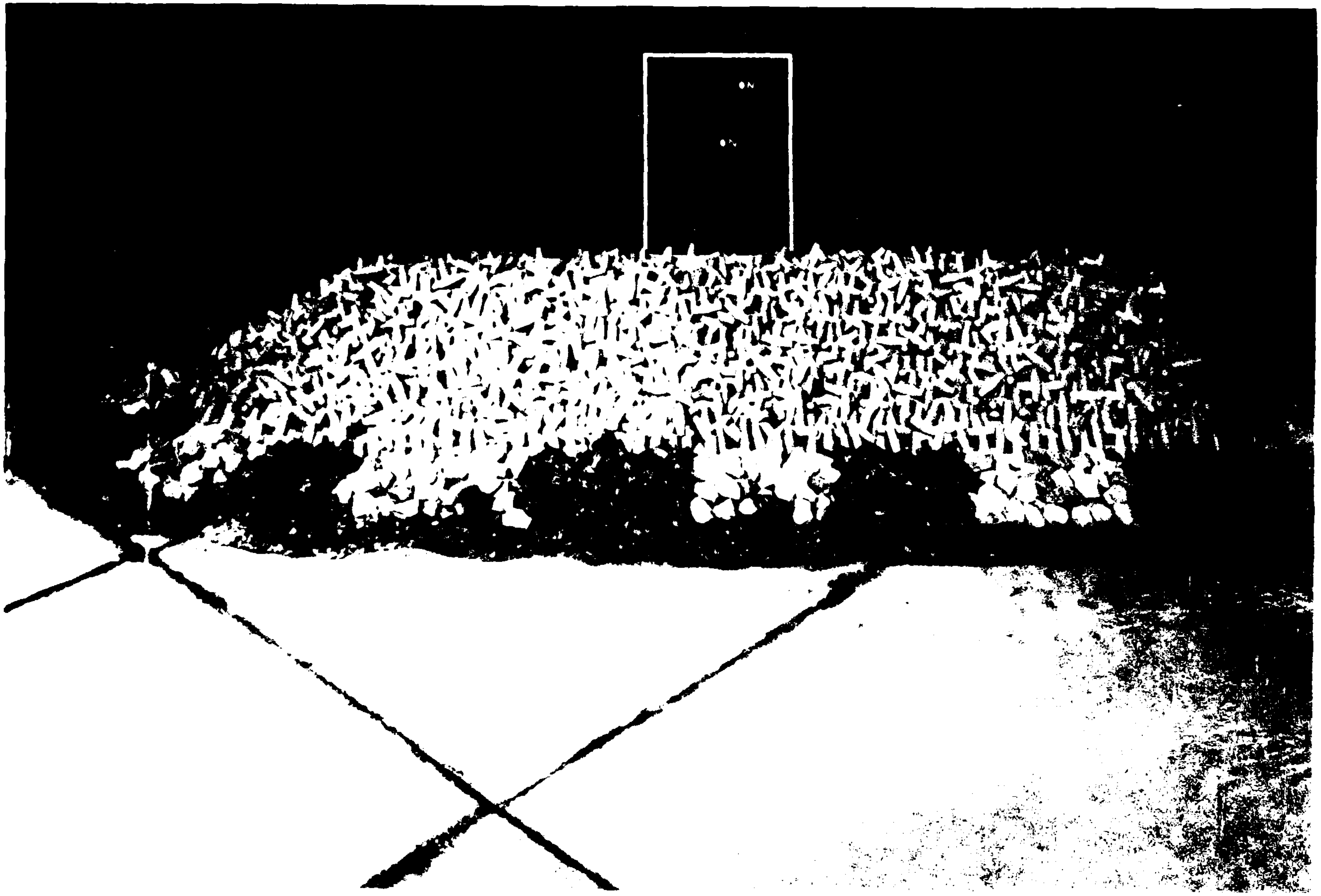

Photo 1. Seaside view after attack of 1.90 sec, 0.37-ft waves; d = 0.40 ft; angle of wave attack = 45 deg

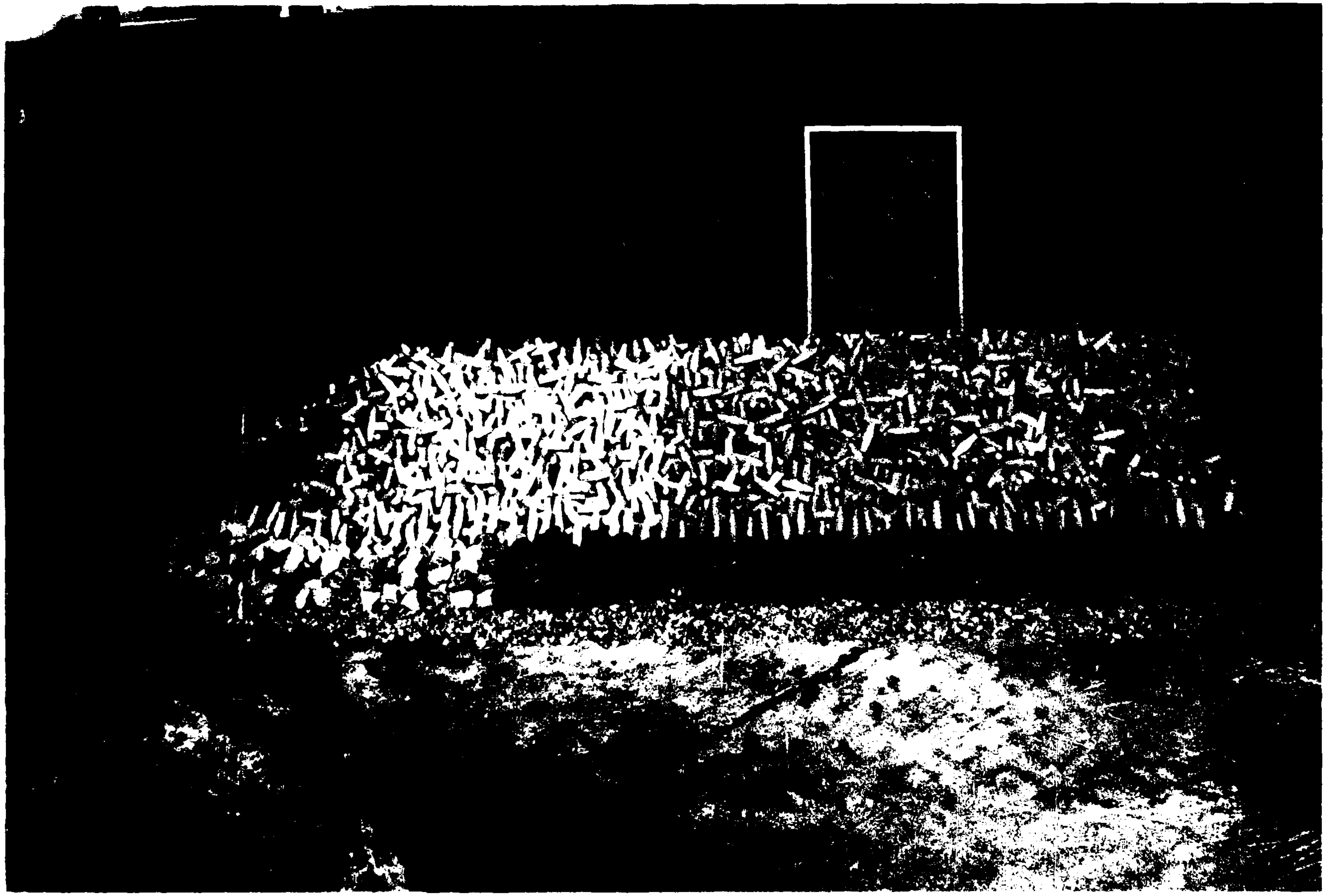

Photo 2. Seaside view after attack of 2.12 sec, 0.39-ft waves; d = 0.50 ft; angle of wave attack = 45 deg

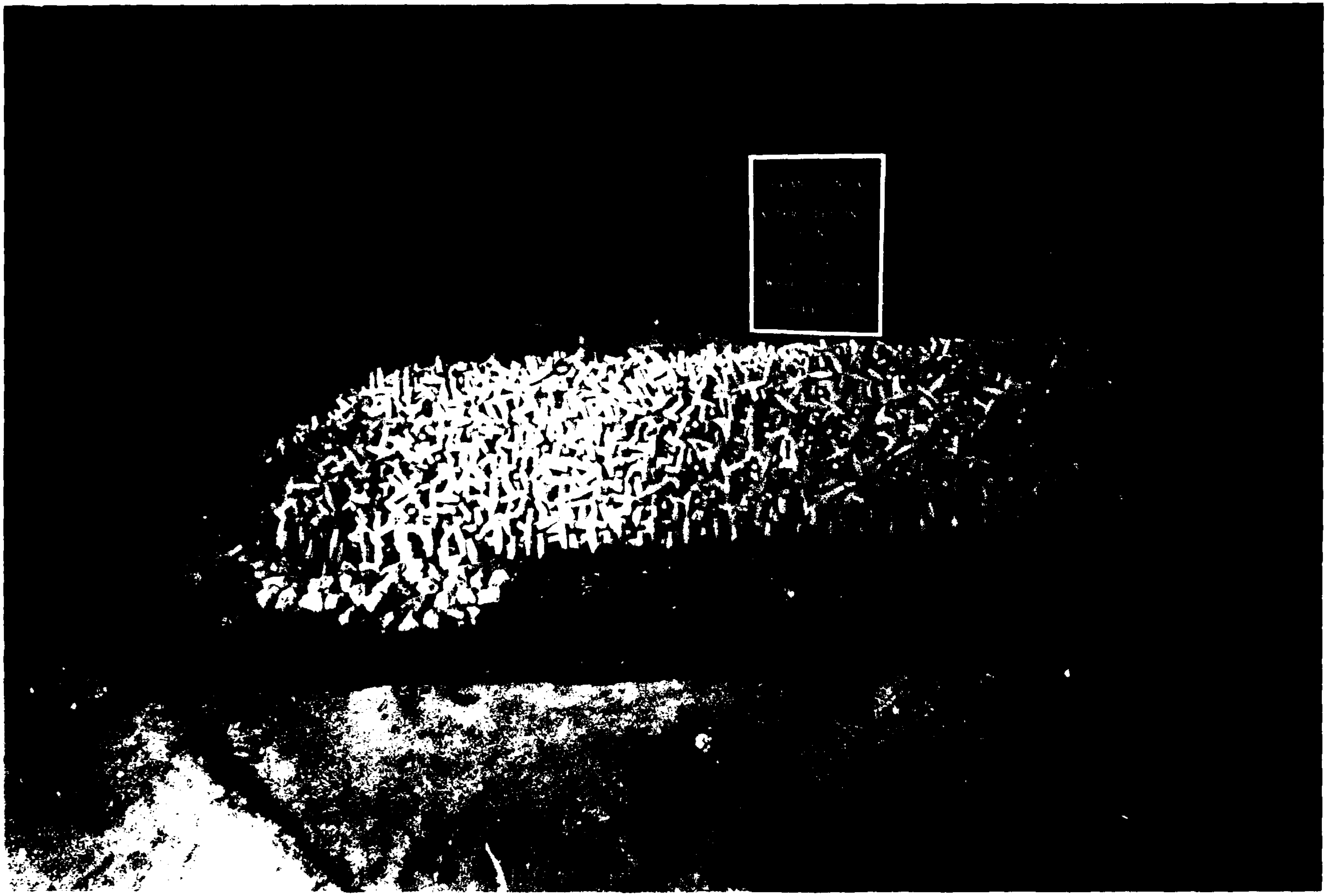

Photo 3. Seaside view after attack of 1.45 sec, 0.45-ft waves; d = 0.60 ft; angle of wave attack = 45 deg

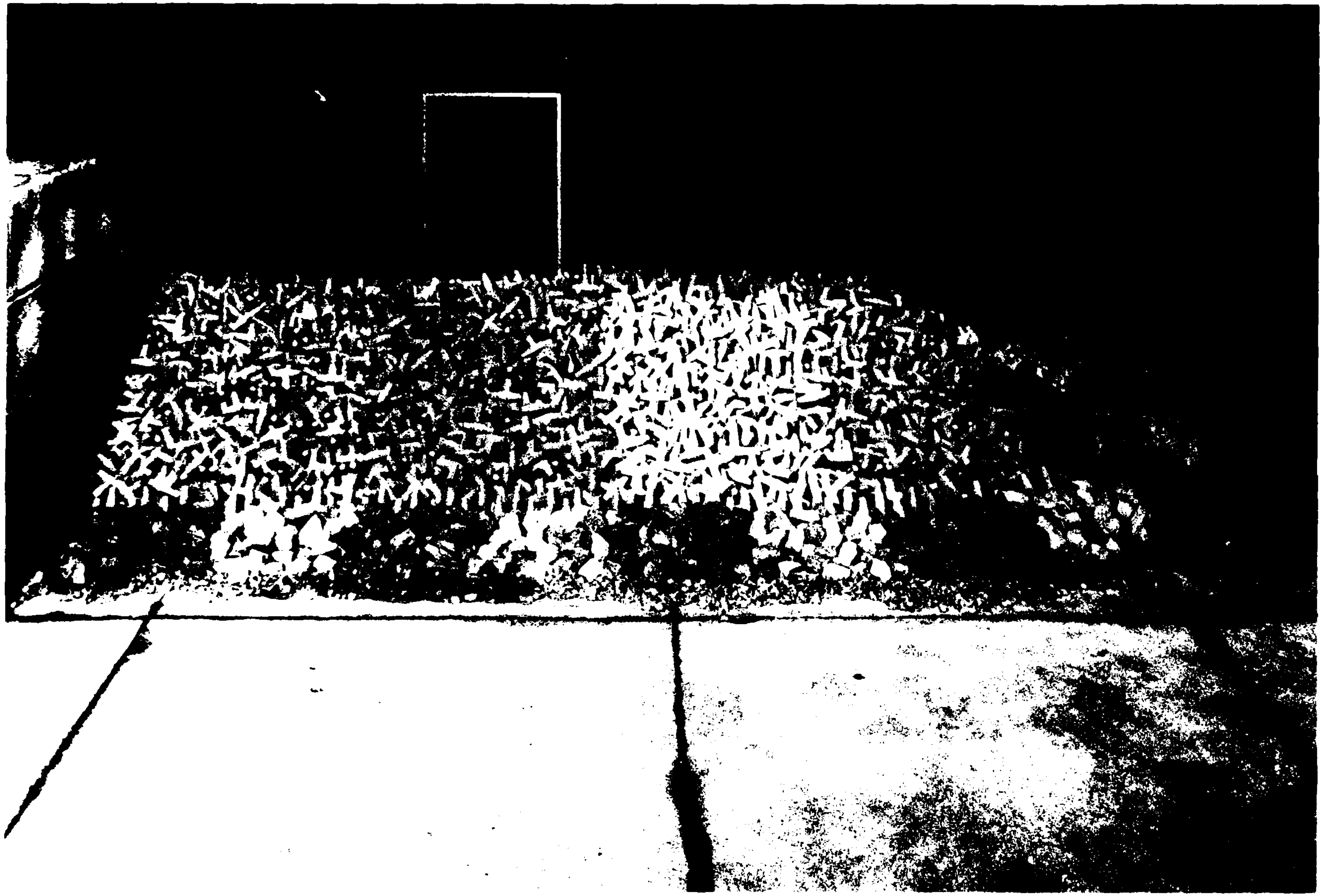

Photo 4. Seaside view after attack of 1.90 sec, 0.37-ft waves; d = 0.40 ft; angle of wave attack = 90 deg

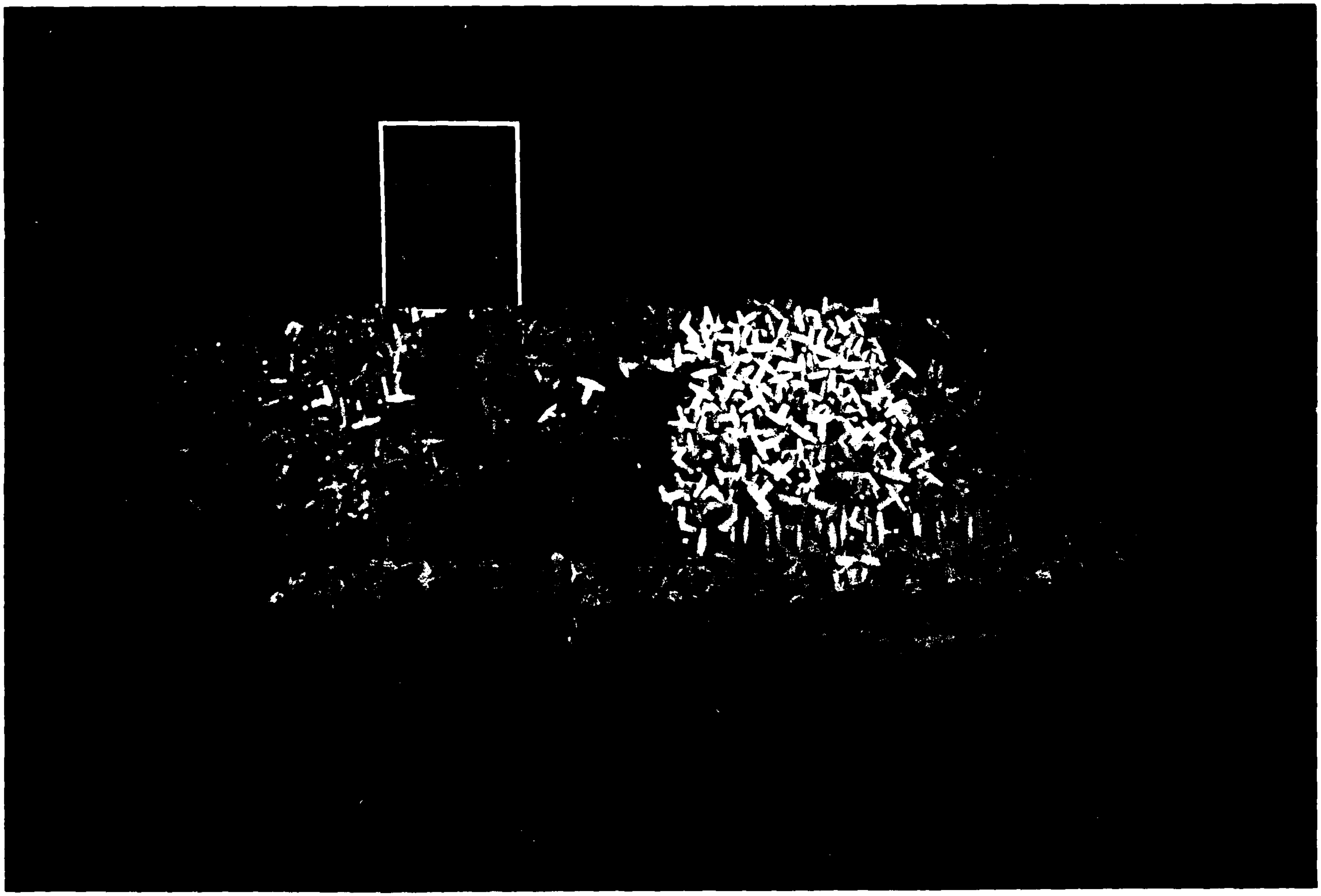

Photo 5. Seaside view after attack of 2.12 sec, 0.39-ft waves; d = 0.50 ft; angle of wave attack = 90 deg

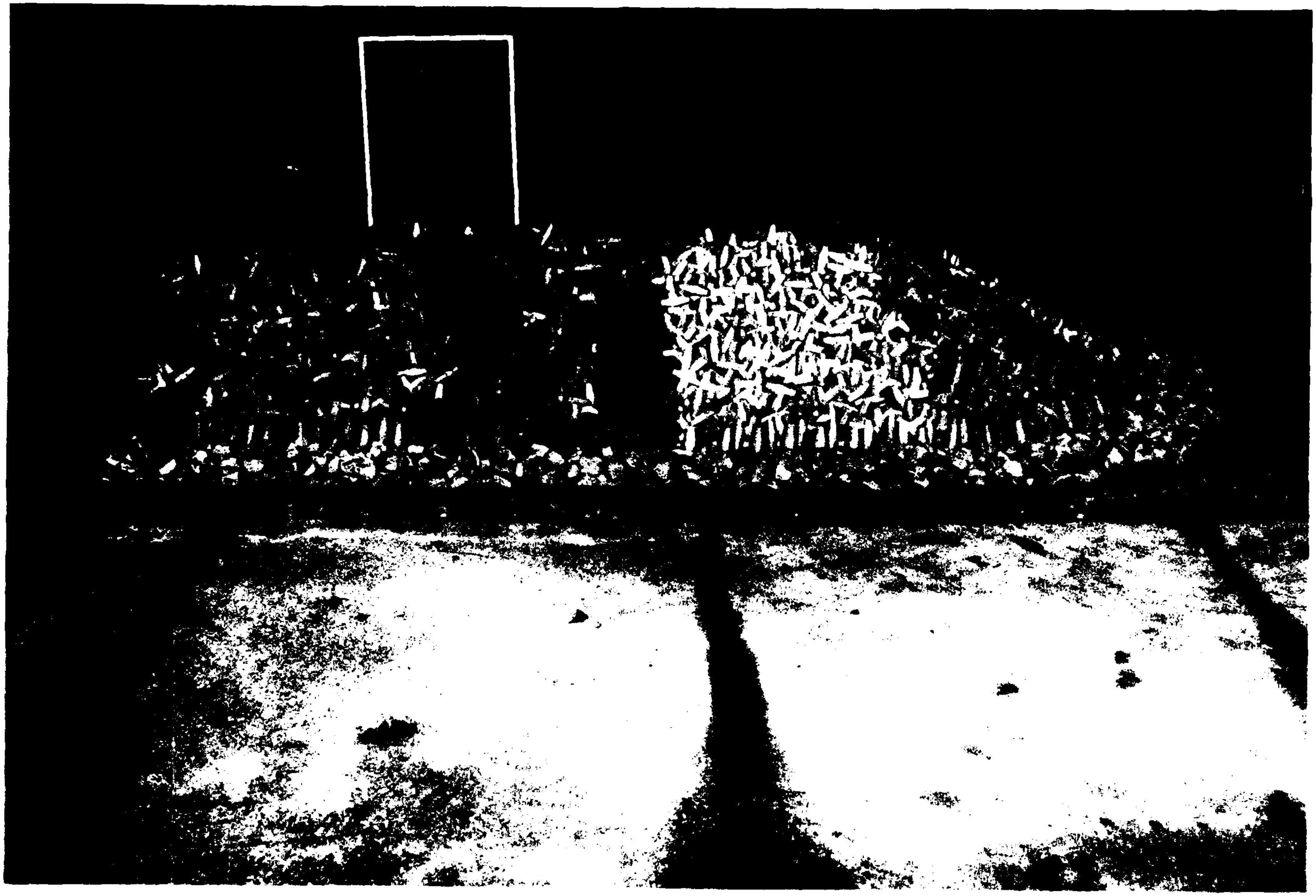

Photo 6. Seaside after attack of 1.45 sec, 0.47-ft waves; d = 0.60 ft; angle of wave attack = 90 deg

APPENDIX A: NOTATION

d	Water depth, ft
d/L	Relative depth, dimensionless
g	Acceleration due to gravity, ft/sec^2
H	Wave height, ft
H/d	Relative wave height, dimensionless
K_D	Stability coefficient, dimensionless
l_a	Characteristic length of armor unit, ft
L	Wavelength in water depth (d), ft
N_s	Stability number = $(\gamma_a^{1/3} H)/W_a^{1/3}(S_a - 1)$
R_N	Reynolds stability number, defined by Equation 1
S_a	Specific gravity of armor unit relative to water in which it is placed
T	Wave period, sec
W_a	Weight of an armor unit, lb
α	Reciprocal of breakwater slope, dimensionless
β	Angle of wave attack, degrees
γ_a	Specific weight of armor unit, pcf
ν	Kinematic viscosity of experimental fluid medium, ft^2/sec